SOLAR MAGNETIC PHENOMENA.[1]

By GEORGE E. HALE.

(*Read April 24, 1914.*)

The discovery by Stark of the electrical analogue of the Zeeman effect establishes a new point of view for the solar physicist. It is now known that an electric field, like a magnetic field, may cause the spectral lines of a light-source placed within it to break up into several components. Furthermore, these components, when observed at right angles to the lines of force, are plane polarized in both cases. Thus there are important points of resemblance between the Zeeman and Stark effects, and it becomes necessary to review the evidence on which the proof of the existence of solar magnetism is based. Is it possible that electric fields, rather than magnetic fields, are responsible for the observed spectroscopic phenomena?

Fortunately, as a brief consideration of the observations will show, this evidence is not open to the charge of ambiguity. The phenomena described in my papers on the magnetic fields of sun-spots and the general magnetic field of the sun are unmistakably those of the Zeeman effect. They are clearly ascribable, in their broad features, to magnetic rather than to electric fields, and if the latter exercise a secondary influence, it is not easily recognizable.

Here an important opportunity for further research is presented. The separation of electrons in sun-spots should give rise to electric fields, which may be sufficiently intense to produce an appreciable Stark effect. Other regions of the solar atmosphere where the conditions are most favorable for the production of electric fields are also open to investigation. But our knowledge of the spectroscopic

[1] Abstract. The complete details of the paper, which will be published in a series of articles in the *Astrophysical Journal,* include the results of investigations on the radial and tangential spot field; the rate of change of field-strength with level, both for spots and the general field; the relationship between field-strength and spot area; the complex fields of spot groups; the phenomena of bipolar spots, etc.

phenomena of all of these regions indicates that special methods of research will be required. It is true that the components of the hydrogen lines are much more widely separated by Stark's electric fields than by any magnetic fields yet produced. But electric fields sufficiently intense to produce such separation do not appear to exist in the sun.[2] Furthermore, when the observations can be made along the lines of force, it is easier to detect a magnetic field giving incomplete resolution of a line than an electric field causing equal overlapping of its constituent parts. This is because of the right-handed and left-handed polarization of the components: a characteristic feature which distinguishes the Zeeman effect from all other spectroscopic phenomena. The use of a quarter-wave plate in conjunction with a Nicol prism permits either component to be extinguished at will. Thus line displacements may be produced which are measurable with such precision as to disclose the existence of a magnetic field of only a few gausses. In fact, it might even be feasible, with special appliances, to detect the earth's field in this way. The absence of circular polarization prevents the observation of such displacements in the Stark effect, but the use of suitable apparatus may ultimately bring to light solar electric fields much weaker than those near the cathode of an ordinary vacuum tube. In any event, it will become possible to set an upper limit to the intensity of the electric fields existing in various parts of the sun.

Let us now review the evidence indicating the presence of magnetic fields in sun-spots, after recalling the hypothesis which led to the application of the tests for the Zeeman effect on Mount Wilson in 1908. This hypothesis, based on the forms and motions of the dark hydrogen ($H\alpha$) flocculi revealed a few weeks earlier with our five-foot spectroheliograph, holds that sun-spots are vortex phenomena. The electrons emitted at high solar temperatures, if whirled in a vortex, must produce a magnetic field, assuming the positive and negative electrons to be unequal in number. The recent work of Harker justifies the view that negative electrons would flow from the hot vapors surrounding the vortex toward the cooler

[2] Unless the widening of lines in the chromosphere, especially that associated with eruptive phenomena, where strong electric fields may be present, should prove to be due in part to their influence.

vapors within it, thus providing the separation called for in the hypothesis. As for the existence of the vortex, in a form different from that first assumed, it is abundantly confirmed by the discovery of Evershed, and the subsequent observations of Evershed and St. John on the motion of vapors in the solar atmosphere surrounding spots.

Assume the axis of the vortex to coincide approximately with a solar radius. Then, if the spot were central on the sun, the lines of force at its center would lie in the line of sight. Such an iron line as λ 6302.709, which is resolved by a magnetic field into three components, should then appear in the spot as a doublet, the central component being absent when observed along the lines of force. The two outer components should be circularly polarized in opposite directions, and it should be possible to extinguish either one at will with the aid of a Nicol prism and quarter-wave plate. Furthermore, two spot vortices rotating in opposite directions should show the opposite components of the line, with the same adjustment of the polarizing apparatus.

This test was successfully applied, and has since been repeated on many sun-spots. Under the most favorable conditions, either component can be completely extinguished. In general, however, the observations cannot be made exactly along the lines of force, and under such circumstances the elliptically polarized components are not completely cut off. Moreover, such a line as λ 6302.709 usually appears as a triplet, the relative intensities of the central and side components varying, as would be expected from the Zeeman effect, with the angle between the lines of force and the line of sight.

Speaking generally, this angle should increase as the spot approaches the sun's limb. We should therefore be able in this case to distinguish the phenomena of plane polarization, since in the laboratory the three components are plane polarized when observed normal to the lines of force. As the central component is polarized in a plane at right angles to the plane of polarization of the side components, it should be possible to extinguish this line in the spectrum of a spot near the limb by rotating the Nicol prism, used without quarter-wave plate. This experiment has been successfully performed.

I need not dwell here on the other evidences of the Zeeman effect, but the proof is very complete. The resolution of the spot lines is not sufficiently perfect to permit the numerous components shown in some cases by laboratory observations to be detected, but triplets and quadruplets can be distinguished, and the resemblance of the observed effects to those of a magnetic field is very close for all lines. One of the most important tests is afforded by the steady decrease in the average separation of the components toward the violet, corresponding with the fact that in a magnetic field their separation is proportional to the square of the wave-length. Here we have a marked disagreement with the Stark effect, where the separation of the components *increases* toward the violet.

In the case of the sun's general magnetic field, my conclusions are also based exclusively upon displacements due to circular or elliptical polarization. This field, which is about eighty times as intense as that of the earth, but of only about one hundredth of the intensity of the maximum sun-spot field, is quite insufficient to separate the solar lines. In fact, the widening which it produces is much too small to be detected, and it is only through the possibility of cutting off one or the other component, and thus of producing a slight shift, that it can be measured.

In the Stark effect the absence of circular or elliptical polarization compels us to seek for evidence presented by changes in the width of lines. The hydrogen lines $H\beta$ and $H\gamma$, when observed for the transverse effect, have been shown by Stark to have five components, the three inner polarized at right angles, the two outer parallel to the field. In the longitudinal effect the two outer components are absent, while the three inner components are present but unpolarized. In the general electric field of the sun the lines of force may be regarded as radial. Hence all lines having Stark effects similar to those of the hydrogen lines should be wider near the limb than at the center of the sun, and their plane polarized outer edges should be capable of extinction by a Nicol. Lack of symmetry in the distribution of the components of a line, such as Stark has observed in some cases, would cause a shift of the lines near the limit. Tests made some time ago, in connection with the study of the

Zaeman effect, indicate that the well-known widening and displacement of the solar lines near the limb are not due primarily to this cause, though there may prove to be a second order effect smaller than I have yet been able to recognize.

A compound half-wave plate, made of narrow strips of half-wave mica, so mounted that (when used with a Nicol) the alternate strips will transmit light polarized in planes at right angles to one another, is to be strongly recommended for this purpose. This will permit the widths and the positions of the solar lines to be compared on a single photograph, in the way which has proved so advantageous in the study of the sun's general magnetic field.[3]

In a preliminary study of our photographs of sun-spot spectra, some of which were taken with the Nicol alone, I have been unable to detect any promising evidence of the Stark effect. However, these plates are poorly adapted for the purpose, and the investigation will soon be continued, and extended to various parts of the solar atmosphere.

[3] Contributions from the Mount Wilson Solar Observatory, No. 71.